

EDWARD TELLER AND NUCLEI: ALONG THE TRAIL TO THE NEUTRINO

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I discuss two of Edward Teller's contributions to nuclear physics, the introduction of the Gamow-Teller operator in β decay and the formulation of the Goldhaber-Teller model for electric dipole transitions, in the context of efforts to understand the weak interaction and the nature of the neutrino.

Keywords: Edward Teller; beta decay; neutrino properties; axial currents; electric dipole nuclear responses.

1. Introduction

It is a great pleasure to take part in the Edward Teller Centennial Symposium and to have this opportunity to describe Dr. Teller's contributions to electroweak nuclear physics. His career in physics began just at the time that the nature of β decay and the likely existence of the neutrino were first becoming clear. Edward's own contributions to this story are very significant and involve both neutrino properties and the role of weak interactions in astrophysics.

Experiments on radioactive nuclei had, by the late-1920s, demonstrated that the positrons emitted in β decay were produced in a continuous spectrum, carrying off on average only about half of the nuclear decay energy.¹ James Chadwick first obtained this result in 1914 from studies of the beta decay of ^{214}Pb . A particularly definitive calorimetry measurement was done by Ellis and Wooster in 1927 and confirmed and improved by Meitner and Orthman in 1930. Speculative explanations included Niels Bohr's suggestion that Einstein's mass/energy equivalence might not hold in the "new quantum mechanics," and Chadwick's observation that perhaps some unobserved radiation accompanied the positron.

In 1930 Wolfgang Pauli, who Bohr had once described as a “genius, comparable perhaps only to Einstein himself,” hypothesized that an unobserved, neutral, spin-1/2 “neutron,” later renamed the neutrino by Fermi, accounted for the apparent anomaly – a new particle with a mass less than 1% that of the proton. His suggestion came in a letter to the participants of a conference in Tuebingen that began with “Liebe Radioaktive Damen und Herren!” Reflecting perhaps the more conservative nature of theorists of that era, he later worried: “I have done a terrible thing. I have postulated a particle that cannot be detected.” Pauli first public presentation on the neutrino did not come until the 1933 7th Solvay Conference.²

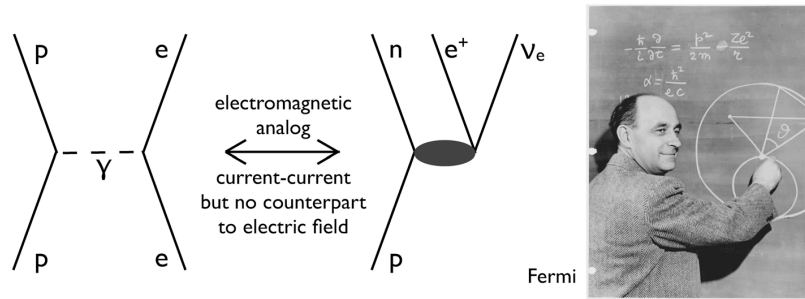


Fig. 1. The four-fermion interaction Fermi proposed as a model for β decay, an analog of the electromagnetic interaction apart from the absence of the electromagnetic field. Photo of Fermi (note the blackboard error) courtesy of Argonne National Laboratory.

Today’s neutron was found by Chadwick in 1932. Fermi, who had followed Pauli’s suggestion and other developments in β decay, in 1934 proposed a model of the weak interaction, based on an analogy with electromagnetism.³ As shown in Fig. 1, a proton bound in a nucleus is transformed into a neutron, with the emission of a positron and ν_e . The interaction occurs at a point, so Fermi’s model has no counterpart to the electromagnetic field. Remarkably, apart from axial currents and the associated parity violation, this description is the correct low-energy limit of today’s standard model. It anticipated future developments in which the electromagnetic and weak interactions would be unified, in the standard model and in the nuclear response to these interactions.

2. Teller⁴ and Gamow⁶

Edward Teller completed his PhD in Leipzig in the same year, 1930, that Pauli made his suggestion of the neutrino. Teller worked with Werner Heisenberg on the quantum mechanics of molecular hydrogen, and had benefited from the many visitors attracted to the university. One of special note was George Gamow, who visited in 1930, accompanied by Lev Landau. Gamow had described barrier penetration in 1928 to explain α decay, setting the stage for later treatments of nuclear astrophysics and the Gamow peak.

Teller became an assistant at Göttingen in 1931, helping Eucken and Franck. Through his friendship with Czech physicist George Placzek, Teller received an invitation to visit Fermi in the summer of 1932. Teller describes the circumstances:⁵

Placzek wanted to continue with his work in the holidays while Göttingen was closed. I wanted to go home to Budapest and he said: "No. I, Placzek, want to visit with Fermi in Rome and you come along." In a way, I was interested but I had just started to make my own money, needed little help from home. Didn't know quite how to pay for my stay in Rome. "Oh said Placzek – I will take care of that. I'll ask Fermi." Here I get a copy of a letter from Fermi, that he has written to appropriate authorities in Hungary – I hear that Dr. Teller is considering to visit Rome for a few weeks. He is a very famous physicist, and I want his cooperation. Could you please help him to get to Rome and to stay there? Fermi and I had never met. That he had reason to consider me as a famous physicist was, to say the very least, an impudent exaggeration. But what makes the story particularly enjoyable for me is that together with the copy of the letter to the Hungarian authorities, I got, attached, a little note from Fermi: Dear Dr. Teller, I am sending you this copy. I want you to know that actually I would be really very happy to see you in Rome. So he took back the exaggeration but replaced it with a, a premature offer to friendship which, of course, became a very real friendship in the course of time.

This must have been an exciting summer to have visited Fermi. A third visitor, Hans Bethe, had also been invited. The neutron had been discovered a few months earlier. (Teller later notes that Fermi's studies of neutron interactions with nuclei, begun in 1934 and revealing the odd activation of uranium, could have profoundly affected world politics, had Fermi correctly

interpreted the results.)

Teller's friend Gamow had resolved to leave Russia by this point. In 1932 he made two attempts to defect by kayak with his wife, Lyubov Vokhminzeva, first via the Black Sea to Turkey, and later from Murmansk to Norway. Both attempts failed because of poor weather conditions. But in 1933 a simpler opportunity arose when both were granted visas to leave Leningrad to attend the 7th Solvay Conference – they same conference where Pauli finally discussed the neutrino. By 1934 Gamow had moved to the US to join the faculty at George Washington University.

Teller's path led him, after two years in Göttingen, to England in 1933, a move facilitated by the Jewish Rescue Committee. He soon arrived in Copenhagen to spend a year with Niels Bohr. In February 1934 he married Augusta Maria Harkanyi, the sister of a friend. In 1935, at the behest of Gamow, Teller was invited to become a professor at George Washington University. He remained there for the next six years. In March 1936 Gamow and Teller submitted a paper on β decay to the Physical Review arguing that a spin-dependent interaction – an axial current – was required to account for observed selection rules.

3. Gamow-Teller Transitions

The Gamow-Teller paper's abstract reads⁷

§1. The selection rules for β -transformations are stated on the basis of the neutrino theory outlined by Fermi. If it is assumed that the spins of the heavy particles have a direct effect on the disintegration these rules are modified. §2. It is shown that whereas the original selection rules of Fermi lead to difficulties if one tries to assign spins to the members of the thorium family the modified selection rules are in agreement with the available experimental evidence.

Fermi's treatment of β decay in analogy with electromagnetism predicts that weak transitions will obey the selection rules of a vector current, which in contemporary notation are displayed in Table 1. In the nonrelativistic, long-wavelength limit – the allowed limit – only the $\mu = 0$ charge operator arises, with selection rules

$$\Delta J = 0 \quad \Delta \pi = 0, \quad \text{e.g., } 0^+ \leftrightarrow 0^+.$$

The Gamow-Teller paper also notes that Fermi had introduced, to ensure relativistic invariance, the velocity operator \vec{p}/M , with selection rules

$$\Delta J = 0, \pm 1 \text{ but no } 0 \leftrightarrow 0 \quad \Delta \pi = 1, \quad \text{e.g., } 0^+ \leftrightarrow 1^-.$$

These operators are shown in the first row of Table 1.

Table 1. Long-wavelength vector-current operators, first-order corrections proportional to $k\vec{r}$, and long-wavelength axial-vector operators.

	$\mu=0$	$\mu=1,2,3$
$J_\mu^V(\vec{r})$	1	\vec{p}/M
$J_\mu^V(\vec{r}) e^{i\vec{k}\cdot\vec{r}}$	$k\vec{r}$	$k[\vec{r} \otimes \vec{p}/M]_{J=0,1,2}$
$J_\mu^A(\vec{r})$	$g_A \vec{\sigma} \cdot \vec{p}/M$	$g_A \vec{\sigma}$

Gamow and Teller considered an additional operator arising from the three-momentum transferred to the nucleus, obtained from a spherical harmonic expansion of $e^{i\vec{k}\cdot\vec{r}}$. The first entry in the second row of Table 1, the dipole operator, is first-forbidden, suppressed by one power of \vec{k} , with the same selection rules as the velocity operator. Its matrix elements can be related to those of the velocity operator through current conservation. (This operator is the subject of another famous Teller paper, discussed later in this talk.) Gamow and Teller argued that β -decay rates for such an operator would be suppressed typically by $\sim 10^{-3}$. They did not discuss explicitly the second-forbidden operator appearing in the second row, which could mediate $0^+ \leftrightarrow 1^+$ transition, but would be suppressed by an additional factor of $\sim 10^{-2}$ due to relativity, as nucleon velocities in the nucleus are of order $|\vec{v}/c| \sim 0.1$. But certainly they would have recognized that this operator exists and is numerically insignificant.

Because the selection rules for allowed and first-forbidden operators built on the vector current could not explain strong magnetic transitions seen in β -decay experiments, Gamow and Teller introduced second allowed operator, the spin operator corresponding to the space-like part of an axial-vector current $J_\mu^A(\vec{r})$, as shown in the third row of Table 1. The selection rules for this operator are

$$\Delta J = 0, \pm 1 \text{ but no } 0 \leftrightarrow 0 \quad \Delta \pi = 0, \text{ e.g., } 0^+ \leftrightarrow 1^+.$$

Gamow and Teller designated the Fermi operator – the vector charge operator – $M1$ and the new Gamow-Teller operator – the axial three-current – $M2$, noting

Either the matrix element $M1$ or the matrix element $M2$ or finally a linear combination of $M1$ and $M2$ will have to be used to calculate the probabilities of the β -disintegrations. If the third possibility is the correct one, and the two coefficients in the linear combination have the same order of magnitude, then all transitions [satisfying

the selection rules] would now lie on the first Sargent curve.

The first Sargent curve is the term then used to designate a strong, allowed transition.

This observation is remarkable in several ways. It gives the correct allowed rate in the absence of polarization

$$\omega \sim |\langle f|1|i\rangle|^2 + g_A^2 |\langle f|\vec{\sigma}|i\rangle|^2.$$

Gamow and Teller suggested that the vector and axial coupling might be similar in magnitude. Today's standard model describes the coupling to the underlying quarks as $V - A$. Also, while the following issue does not arise for rates – the focus of the Gamow-Teller paper – one could accomplish the suggested generalization of Fermi's theory in two ways. In a modern notation,

$$J_\mu^V J^{V\mu} \rightarrow \begin{cases} J_\mu^V J^{V\mu} + J_\mu^A J^{A\mu} \\ (J_\mu^V - J_\mu^A)(J^{V\mu} - J^{A\mu}) \end{cases}$$

That is, one could add an axial current-current interaction to Fermi's vector-vector interaction, or alternatively generalize the current to $V - A$. The latter would have anticipated by 20 years parity violation in the weak interaction. While Gamow and Teller do not comment explicitly on this issue or mention parity violation, their description of the matrix elements $M1$ and $M2$ is curious. They speak of a linear combination of $M1$ and $M2$ – that is, a sum of vector and axial-vector amplitudes, which they suggest would be of comparable importance. They were remarkably close to the standard model.

The introduction of the Gamow-Teller operator was critical to efforts in the 1930s to understand the mechanisms for hydrogen burning in main-sequence stars. The initiating step in the pp chain synthesis of ${}^4\text{He}$

$$p + p \ (L = 0 \ S = 0 \ T = 1) \rightarrow d \ (L = 0 \ S = 1 \ T = 0) + e^+ + \nu_e$$

is a Gamow-Teller transition.

The structure of the weak interaction – the amplitudes that might be constructed from vector (V), axial-vector (A), scalar (S), pseudoscalar (P), and tensor (T) terms at low energies – was not fully resolved until 30 years later. Teller had another connection with this story, through his University of Chicago student C. N. Yang (1946-9). In 1957 Lee and Yang pointed out that parity conservation was poorly established in the weak interaction, and that its violation might explain puzzling decay properties of neutral kaons. Quickly following this suggestion Wu, Ambler, Hayward, Hoppes,

and Hudson found an angular asymmetry in the β s produced in the decay of polarized ^{60}Co , and Garwin, Lederman, and Weinrich found highly polarized muons in pion β decay. Finally, Goldhaber, Grodzins, and Sunyar demonstrated that β decay neutrinos are left-handed, ruling out possibilities like S+T in favor of V-A.

4. Particles, Antiparticles, and Neutrino Mass

While the $V-A$ nature of the weak interaction may seem an old story, it has a modern connection to some very important open questions regarding the neutrino. The neutrino is unique among standard model fermions in that it lacks a charge or any other additively conserved quantum number. Such quantum numbers reverse sign under particle-antiparticle conjugation, and thus distinguish particles from their antiparticles. Thus we know that the electron has a distinct antiparticle, the positron with its opposite charge. But in the case of the neutrino, the need for a distinct antiparticle is unclear: it is possible that the neutrino is its own antiparticle.

This might prompt one to do the gedanken experiment illustrated in the top panel of Fig. 2. The first step is to define the ν_e as the particle that accompanies the positron produced by a β^+ source. The second step is to determine what that particle does when it strikes a target. One finds it produces e^- s.

Next define the $\bar{\nu}_e$ as the particle that accompanies the electron produced by a β^- source. Then one finds that this particle, on striking a target, produces an e^+ . From a comparison of the two experiments it appears that the ν_e and $\bar{\nu}_e$ are distinct particles: they produce different final states when they interact in targets.

As there is no obvious quantum number distinguishing the ν_e and $\bar{\nu}_e$, would would then be tempted to introduce one, the lepton number l_e , requiring it to be additively conserved:

$$\begin{array}{rcl}
 \text{lepton} & l_e & \\
 e^- & +1 & \\
 e^+ & -1 & \\
 \nu_e & +1 & \\
 \bar{\nu}_e & -1 &
 \end{array}
 \quad \Leftrightarrow \quad
 \sum_{in} l_e = \sum_{out} l_e.$$

This would account for the results of the “experiments” illustrated in Fig. 2. Historically this issue was connected with the early development of the Cl detector famous in solar neutrinos. After Pontecorvo suggested using Cl, Alvarez investigated various background issues, as he was considering

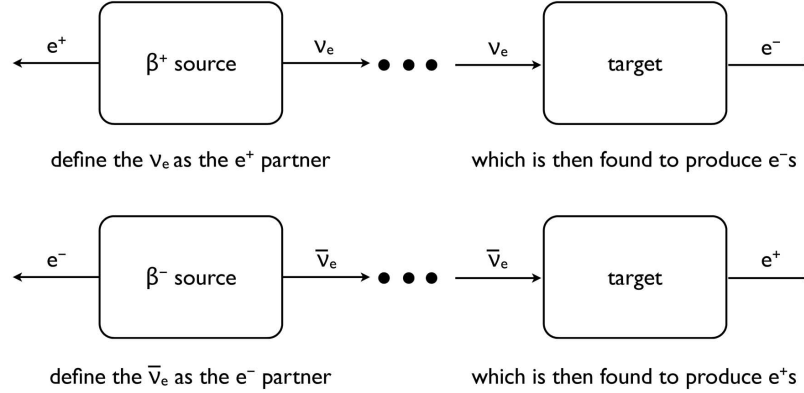
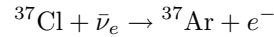


Fig. 2. An operational test of the identity of the ν_e and $\bar{\nu}_e$, prior to the discovery of parity nonconservation. If one were to define the ν_e as the partner of the positron in β^+ decay and the $\bar{\nu}_e$ as the partner of the electron in β^- decay, then these neutrinos would appear to be distinct operationally, when their interactions in targets are tested. This would seem to require the introduction of a quantum number like lepton number to distinguish the ν from the $\bar{\nu}$.

testing $\nu/\bar{\nu}$ identity, using reactor $\bar{\nu}_e$ s. Later Davis placed a Cl detector prototype near the Savannah River reactor to search for



but found no Ar, indicating that the ν_e and $\bar{\nu}_e$ are distinct at the level of $\sim 5\%$.

There is an elegant way to do the Savannah River experiment at the nuclear level, with neutrinoless $\beta\beta$ decay.⁸ In this process a nucleus (N, Z) decays through a second-order weak interaction

$$(N, Z) \rightarrow (N - 2, Z + 2) + e^- + e^-$$

with the emission of two electrons. If the ν_e and $\bar{\nu}_e$ are identical – if the neutrino is a Majorana particle – then the neutrino emitted in one neutron β decay can be reabsorbed on a second neutron, as shown in the upper panel of Fig. 3. But we do not see this process in nature. Thus it seems once again that the ν_e and $\bar{\nu}_e$ must be distinct, carrying opposite lepton charges. As the middle panel illustrates, neutrinoless double β decay would then be strictly forbidden: the final state of two electrons ($l_e = 2$) cannot result from the decay of an initial state with $l_e = 0$.

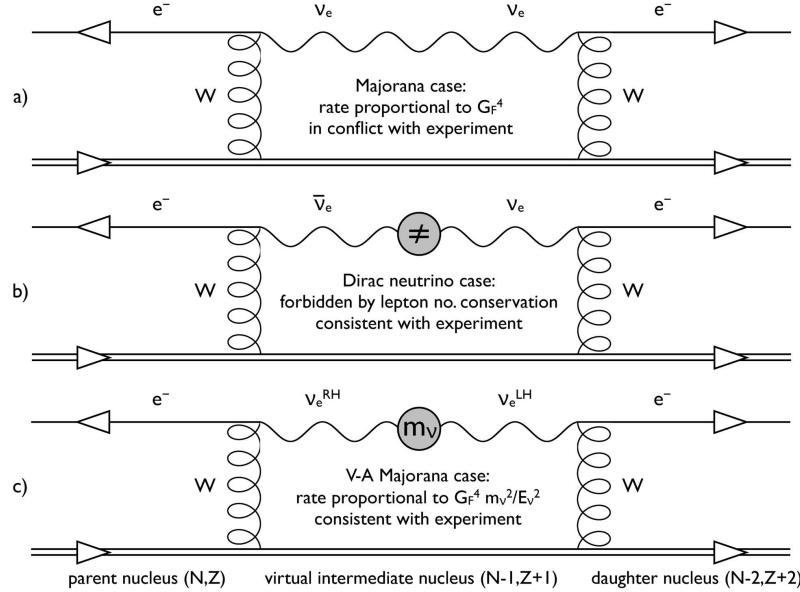


Fig. 3. Panel a) neutrinoless double beta decay in the case of a Majorana neutrino appears naively to be in conflict with experiment, as it produces a substantial decay rate. In the Dirac case (Panel b)) the decay is strictly forbidden by lepton number conservation: the $\bar{\nu}_e$ produced in the first decay is the wrong neutrino to complete the second step. A Dirac neutrino is thus allowed by experiment, as it is consistent with the absence of neutrinoless double beta decay, a process so far not seen in nature. Panel c) shows the Majorana case, including the effects of neutrino handedness. A Majorana neutrino is allowed by experiment, provided the mass is sufficiently small (so the handedness is sufficiently exact). This requires the Majorana neutrino mass to be $\lesssim 1$ eV, a result compatible with other tests of mass, such as neutrino oscillations.

But there is a hidden assumption in the above arguments, one that starts with the axial current introduced by Gamow and Teller. We can remove all references to lepton number – so that $|\bar{\nu}_e\rangle = |\nu_e\rangle$ – but suppress double β decay with a different label, the handedness of the neutrino. As the Goldhaber, Grodzins, and Sunyar experiment would show in 1957, because the Gamow and Teller spin interaction does appear with Fermi's vector interaction in the combination V-A, the (anti)neutrino emitted in β^- decay is right-handed, while the neutrino that produces an e^- when scattering in a target is left-handed. Thus, in the third panel of Fig. 3, we find another mechanism for suppressing double β decay, without the assumption of a conserved lepton number: the neutrino produced in the first beta decay has

the wrong handedness to generate a neutrino by scattering off a second nucleon.

These assignments do not forbid double β decay – we eliminated lepton number and its absolute conservation – but only suppress it: the handedness of the neutrino is not exact because of its mass. The amplitude in panel c) is proportional to the handedness admixture

$$\frac{m_\nu}{E_\nu} \sim 3 \times 10^{-8} \frac{m_\nu}{1 \text{ eV}},$$

where we have estimated the energy of the exchanged neutrino to be $E_\nu \sim R_{\text{nucleus}}^{-1} \sim 6f^{-1}$ for a typical heavy nucleus. The same arguments apply to the Savannah River experiment and other tests that naively suggest the ν must have a distinct antiparticle.

Thus this discussion shows that there are two descriptions of massive neutrinos, and *both* are consistent with nature, for light neutrinos. These are illustrated in Fig. 4. The first is the two-component Majorana case: the neutrino is its own antiparticle, so that under CPT the $|\nu_{LH}\rangle \rightarrow |\nu_{RH}\rangle$. One can also consider the constraints of Lorentz invariance. If one boosts to a frame moving faster than a massive neutrino, momentum is reversed but not spin. The handedness is then flipped: Lorentz invariance requires a right-handed counterpart to a left-handed state, and the reverse. Thus a two-component neutrino can satisfy the constraints of both particle-antiparticle conjugation and Lorentz invariance.

Alternatively, one can introduce a lepton number to distinguish the ν and $\bar{\nu}$. Lepton number reverses under particle-antiparticle conjugation, but not under Lorentz boosts. Thus four neutrino components are required to satisfy the constraints of particle-antiparticle conjugation and Lorentz invariance. This is the Dirac case of Fig. 4.

Our minimal standard model of particle physics does not allow neutrino mass: Dirac masses are absent because there is no right-handed neutrino field, and Majorana masses are absent because they require interactions that are poorly behaved at high energies. But neither of these standard-model restrictions is likely to hold in the more general models that will someday replace the standard model; nor is the second concern of any importance if one adopts a modern view that the standard model is an effective theory that should be restricted to lower energies.

We now know a new, extended standard model is needed, because neutrinos are massive. The Super-Kamiokande and SNO experiments have demonstrated that atmospheric and solar neutrinos oscillate. While oscillation experiments constrain differences in the squares of neutrino masses,

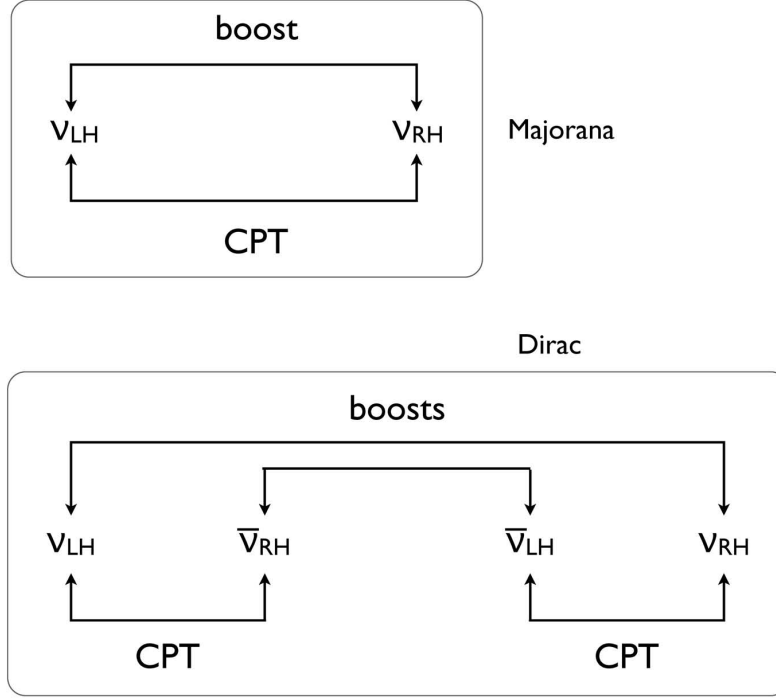


Fig. 4. The two-component (Majorana) and four-component (Dirac) neutrino schemes, showing the relationships between the components under Lorentz boosts and particle-antiparticle conjugation.

those differences tell us that at least one neutrino has a mass $m \gtrsim 0.04$ eV. We also have the ν mass bounds

$$\sum_i m_i \lesssim 6.6 \text{ eV (laboratory)} \quad \sum_i m_i \lesssim 0.7 \text{ eV (cosmology)}$$

The former comes from combining tritium β decay mass limits with mass differences $\delta m^2 = m_i^2 - m_j^2$ known from oscillation experiments, while the latter is derived from cosmological arguments, that massive neutrinos inhibit the growth of structure on large scales.

This chain of argument leads to an interesting observation: while we must look to extended models for an explanation of neutrino mass, it is at first not clear how a more unified theory can account for neutrino masses, since they are so much smaller than the masses of other standard model particles. A group theory factor is not going to generate the factor of 10^{-6}

or more to explain the ratio m_{ν_e}/m_e . But a elegant resolution of this puzzle is provided by the special freedom available with neutrinos, the possibility of both Dirac and Majorana mass terms.⁹ Neutrinos and other standard-model fermions can share the same Dirac mass scale m_D . But the seesaw mechanism, in addition, postulates a heavy right-handed Majorana neutrino mass m_R , yielding a mass matrix

$$\begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \xrightarrow{\text{diagonalize}} m_{\nu}^{\text{light}} \sim m_D \left(\frac{m_D}{m_R} \right)$$

Thus a natural “small parameter” m_D/m_R emerges that explains why neutrinos are so much lighter than other fermions. The scale m_R represents new physics. If one takes

$$\left. \begin{array}{l} m_{\nu} \sim \sqrt{\delta m_{\text{atmos.}}^2} \sim 0.05 \text{ eV} \\ m_D \sim m_{\text{top}} \sim 180 \text{ GeV} \end{array} \right\} \Rightarrow m_R \sim 0.3 \times 10^{15} \text{ GeV},$$

one finds an m_R that is very close to the energy scale where supersymmetric Grand Unified theories predict that the strong, weak, and electromagnetic forces unify. Thus it is quite possible that tiny neutrino masses are giving us our first glimpse of physics that is otherwise hidden by an enormous energy gap.

5. The Goldhaber-Teller Model

In 1946 Edward Teller left Los Alamos to join Enrico Fermi and Maria Mayer at the University of Chicago. In 1948 Maurice Goldhaber, then at the University of Illinois, approached Teller about the broad photoabsorption resonances he had observed in (γ, n) nuclear reactions – the nuclear response was similar to related phenomena in crystal lattices that Teller had considered years earlier. Out of these discussions emerged a simple collective model of the giant dipole resonance in which the neutrons oscillate against the protons, with the nuclear symmetry energy generating a linear restoring force. This single harmonic mode could be constructed to satisfy the energy-weighted $E1$ sum rule

$$\frac{2M}{\hbar^2} \sum_f (E_f - E_{g.s.}) \langle f | \sum_{i=1}^A z(i) \frac{\tau_3}{2} | g.s. \rangle^2 = \frac{A}{4}.$$

Figure 5 illustrates the mode.

This celebrated paper¹⁰ also has a connection with neutrinos and with the Gamow-Teller suggestion of a semi-leptonic weak interactions mediated by a combination of vector and axial-vector currents. Once the model is

constructed to saturate the $E1$ sum rule, it can be generalized algebraically to account for the full 15-dimensional super-multiplet of dipole resonances, if it is assumed nuclear forces are independent of spin and isospin. This yields a set of $SU(4)$ generalizations of the $E1$ mode which saturate the ($L=1$ S T) responses for the allowed choices of spin S and isospin T.

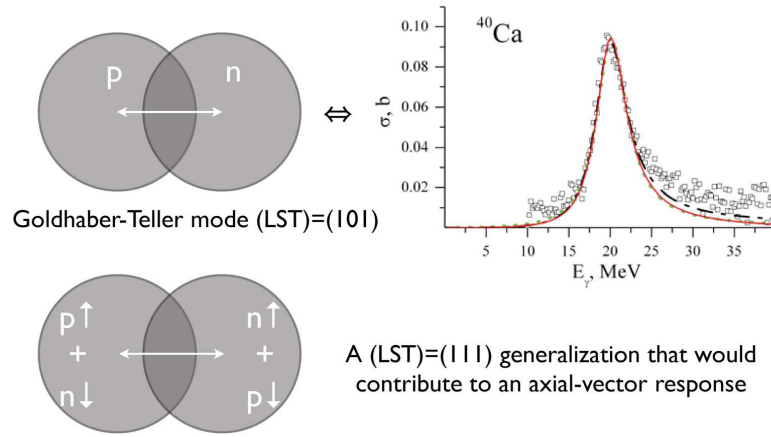


Fig. 5. Schematic illustrations of the original Goldhaber-Teller $E1$ mode, saturating the photoabsorption sum rule, and of an $S=1$ generalization, one of the giant dipole modes that would be excited by the axial-vector current in inelastic neutrino scattering.

One can envision this pictorially as a generalization of the proton/neutron fluid oscillations of the original Goldhaber-Teller model to fluids that also carry spin. For example, the axial responses needed to describe neutral current neutrino scattering involve the substitution

$$z(i)\tau_3(i) \Rightarrow [\vec{r}(i) \otimes \vec{\sigma}(i)]_{J=0,1,2} \begin{pmatrix} \tau_3(i) \\ 1 \end{pmatrix}$$

An example of such a spin-dependent mode is given in Fig. 5: a fluid consisting of spin-up protons and spin-down neutrons oscillates against one with spin-up neutrons and spin-down protons. Thus this is an $L=1$ $S=1$ $T=1$ mode.

Despite its great simplicity, this generalized Goldhaber-Teller model captures enough of the basic physics of first-forbidden nuclear responses to be a useful tool for calculations. One “homework” problem¹¹ that can

be solved with this model is “How did the galaxy make the fluorine found in toothpaste?” That data needed for the solution include:

- Fluorine has a single stable isotope, ^{19}F , and is relatively rare. Its galactic abundance relative to neon is 1/3100.
- Galactic core-collapse supernovae occur about once every 30 years.
- Such supernovae are thought to be the primary source of Ne, which is synthesized from “burning” oxygen in the supernova progenitor star during the long period of hydrostatic evolution, then ejected with the rest of the mantle during the explosion.
- Each supernova releases about 4×10^{57} muon and tauon ν s.
- As these ν s have an average energy of ~ 25 MeV, most can excited giant resonances when scattering off Ne.
- As the typical radius of the Ne shell is about 20,000 km, the total fluence of ν s through this shell during the few seconds of the explosion is $\sim 10^{38}/\text{cm}^2$.

Although the average neutrino energy $\omega \sim 25$ MeV, cross section kinematics yields makes neutrinos on the high-energy tail of the Boltzmann distribution much more important. Furthermore, neutrinos scattering backward can transfer a three-momentum $|\vec{q}| \sim 2\omega$. Consequently the inelastic scattering is dominated by the first-forbidden responses, the giant resonances. While the original Goldhaber-Teller model was designed to saturate the sum rule for the (γ, n) nuclear response, its SU(4) generalization addresses the full set of giant resonances important to both axial and vector currents. That is, it provides a reasonable model for

$$^{20}\text{Ne}(Z_0, n)^{19}\text{Ne} \rightarrow ^{19}\text{F} \quad \text{or} \quad ^{20}\text{Ne}(Z_0, p)^{19}\text{F}.$$

where Z_0 , the boson mediating neutrino-nucleus scattering, is the analog of the γ in Goldhaber’s photoexcitation experiments. Summing over the spin and isospin modes yields

$$\sigma \sim 3 \times 10^{-41} \text{ cm}^2 \Rightarrow 1/300 \text{ of Ne shell converted to F}$$

The direct synthesis of new elements by supernova neutrinos is called the neutrino process. When calculations only slightly more sophisticated than the above are combined with nuclear reaction networks that include the effects of the processing of the neutrons and protons coproduced with the ^{19}Ne and ^{19}F , as well as effects of shock-wave heating of the Ne shell, one finds that the correct ratio of $^{19}\text{F}/^{20}\text{Ne}$ is obtained for a heavy-flavor neutrino temperature of ~ 6 MeV. This is very similar to the temperatures supernova modelers obtain from detailed hydrodynamic simulations.

6. Summary

Edward Teller's career in nuclear physics spanned 70 years and encompassed many subjects not addressed here. However, the two papers chosen for discussion are notable for their physics insight and their historical setting.

Gamow and Teller introduced a spin-dependent β decay amplitude that anticipated the axial-vector current of the standard model and the 1957 discoveries that established the V-A form of the weak interaction. The resulting handedness of the neutrino provides an explanation for suppressed double β decay rates, thereby keeping open the possibility of Majorana neutrino masses. Because neutrinos can have both Majorana and Dirac mass terms, a natural explanation arises for the difference between the neutrino mass scale and that of other fermions – but one not yet confirmed experimentally.

Goldhaber and Teller introduced a simple nuclear model capable of saturating the $E1$ photoabsorption sum rule. This model has a natural generalization for weak charged- and neutral-current responses, if the nuclear Hamiltonian is assumed to be independent of spin and isospin. While the Gamow-Teller paper described for the first time the full set of operators responsible for allowed transitions, and Goldhaber-Teller model and its SU(4) generalization provided a similar description for the first-forbidden responses.

These two papers together provide a framework for tackling astrophysics problems that range from the pp-chain and Big-Bang nucleosynthesis to the interactions of neutrinos in the mantle of a supernova.

7. Acknowledgements

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